Coherently dedispersed gated imaging of millisecond pulsars

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ABSTRACT

Motivated by the need for rapid localisation of newly discovered faint millisecond pulsars (MSPs) we have developed a coherently dedispersed gating correlator. This gating correlator accounts for the orbital motions of MSPs in binaries while folding the visibilities with best-fit topocentric rotational model derived from periodicity search in simultaneously generated beamformer output. Unique applications of the gating correlator for sensitive interferometric studies of MSPs are illustrated using the Giant Metrewave Radio Telescope (GMRT) interferometric array. We could unambiguously localise five newly discovered Fermi MSPs in the *on-off* gated image plane with an accuracy of $\pm 1''$. Immediate knowledge of such precise position allows the use of sensitive coherent beams of array telescopes for follow-up timing observations, which substantially reduces the use of telescope time ($\sim 20\times$ for the GMRT). In addition, precise a-priori astrometric position reduces the effect of large covariances in timing fit (with discovery position, pulsar period derivative and unknown binary model), which in-turn accelerates the convergence to initial timing model. For example, while fitting with precise a-priori position ($\pm 1''$), timing model converges in about 100 days, accounting the effect of covariance between position and pulsar period derivative. Moreover, such accurate positions allows for rapid identification of pulsar counterpart at other wave-bands. We also report a new methodology of in-beam phase calibration using the *on-off* gated image of the target pulsar, which provides the optimal sensitivity of the coherent array removing the possible temporal and spacial decoherences.

Subject headings: pulsars: general $-$ pulsars: individual (J1120$-$3618, J1207$-$5050, J1551$-$0658, J1646$-$2142, J1828+0625) $-$ techniques: interferometric

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1. Introduction

The ongoing sensitive surveys (e.g. Fermi directed radio searches, Ray et al. (2012); Green Bank drift scan Survey[3]; Green Bank North Celestial Cap (GBNCC) survey[4], High Time Resolution Universe (HTRU) survey at Parkes, Keith et al. (2010); Pulsar Arecibo L-Band Feed Array (PALFA) survey, Cordes et al. (2006)) have discovered a number of intriguing fainter millisecond pulsars (MSPs). As a result in last three years the population of Galactic disk MSPs is increased by about 45%[5]. Sensitive follow-up studies of these newly discovered MSPs using coherent beams of array telescopes, or at higher frequencies using single dishes, are hindered by the large uncertainties associated with the discovery positions. For example, discovery uncertainties range from $40'$ for the GMRT at 322 MHz (GMRT$-$322) to $4'$ for the Arecibo at L-band. Sensitive coherent array follow-up observations significantly reduces the use of array telescope time ($\sim 20\times$ for the GMRT), which is important as arrays are the future for large radio telescopes. Such coherent array observations improves the uncertainties in time-of-arrivals (TOAs) and allows to generate much closely spaced TOAs in order to avoid ambiguous phase connection while timing the binaries with shorter orbits. Traditionally long-term pulsar timing programs are used to reduce such positional uncertainties, requiring significant amount of observing time. Simultaneous timing fit with discovery position and unknown binary parameters can be affected from large covariances, specially for long period binaries. In addition, the covariance between position and pulsar period derivative ($\dot{P}$) limits the convergence of timing fit even with known binary model. The effects of such large covariances in timing fit can be minimised with precise a-priori astrometric position.

Being compact objects pulsars are effectively seen as point sources in interferometric imaging. Pulsars specially MSPs are weak radio sources in continuum image plane, having fluxes in the range of few mJy even at lower frequencies. Identification of pulsar counterpart in the continuum image can also be confused with the other sources in the field of view. Considering the narrow duty cycle, 3%$-$10% (Henry & Paik 1969), the detection significance of a pulsating point source can be largely improved by removing the off-pulse noise. This is achieved through pulsar gating, where the continuum image is sampled synchronously with the pulsed signal to generate a number of gated images for different pulse phases (e.g. pulsar gating at the ATCA, Lazendic (1999)). Background sky subtracted *on-off* gated image allows to unambiguously identify the location of pulsed emission (Camilo et al. 2000). However,

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[3]http://www.as.wvu.edu/ pulsar/GBTdrift350/

[4]http://arcc.phys.utb.edu/gbncc/

[5]http://astro.phys.wvu.edu/GalacticMSPs/GalacticMSPs.txt

such precise position determination using gating is hitherto not been reported for MSPs. High time resolution gating requirements for MSPs, with the gating window $\sim 100\ \mu$s, could be computationally challenging. More importantly for MSPs, since period and intrinsic pulse width are quite small, dispersion correction is required to be done (unlike normal pulsars) before such high time resolution gating, in order to account for large dispersion delay. For example, considering a MSP with a dispersion measure (DM) of 30 pc/cc, the dispersion delay at 322 MHz GMRT frequency across 32 MHz band is ~ 247 ms, which is many times of MSP period. In earlier studies gating has been done after correlation using incoherent dedispersion. But incoherent dedispersion smearing across frequency channels can be 5 times larger than intrinsic pulse width (considering a 2 ms MSP at 30 pc/cc DM with 5% duty cycle for GMRT−322), significantly reducing the number of effective gates due to pulse smearing. Thus reconstructing intrinsic pulse width with coherent dedispersion (Hankins & Rickett 1975) will be beneficial while performing gating with larger bin numbers requiring sufficient time resolution. In addition, since majority of MSPs are in binary system, the effect of orbital motion on pulsar period has to be accounted for in MSP gating correlator.

Alternatively localisation of newly discovered pulsars can be achieved by forming multiple coherent beams covering the primary beam of the telescope. For example the grating response of a linear array like the WSRT can be used for localisation with an accuracy of few arcminutes (Rubio-Herrera et al. 2012). Whereas with continuum imaging followed by the multi-pixel beamformer using nonlinear array like the GMRT (Roy et al. 2012) we have achieved the positional accuracy of few arcseconds (determined by the synthesized beam of the array). But this method is not efficient to localise relatively fainter MSPs having very low detection significance in continuum image plane.

In order to improve the detection significance in image plane and to achieve positional accuracy of the order of $1''$, we have developed a coherently dedispersed MSP gating correlator at the GMRT. In addition to aperture synthesis at moderate time constants ($\sim$ seconds) and high time resolution incoherent and coherent beam formation ($\sim 30\ \mu$s), the GMRT Software Back-end (GSB; Roy et al. (2010)) is equipped to stream the raw base-band samples from all the antennas to array of storage disks. In this paper we describe design and implementation of the MSP gating correlator using raw Nyquist sampled base-band data and its application to obtain the precise locations of five newly discovered MSPs from the Fermi directed searches. In addition we demonstrate an unique application of gated imaging, in using pulsar as a phase calibrator to achieve the optimal sensitivity for the coherent array.

2. MSP gating correlator

Design of the MSP gating correlator that can increase the signal-to-noise (S/N) of a pulsar in image plane by a factor of 3 to 6 (approximately proportional to the inverse square root of duty cycle) is described below.

(a) Coherent dedispersion : Since baseline based incoherent dedispersion performed before folding the visibility time-series at the best-fit topocentric model is not adequate for the study of MSPs at lower frequencies, we implement antenna based coherent dedispersion. Antenna based coherent dedispersion ($\sim$ N operations) can also be computationally favorable compared to baseline based incoherent dedispersion ($\sim$ N^2 operations) for the future arrays with large number of elements (N). Coherent dedispersion module is running on the recorded raw base-band data prior to correlation, and is parallelized over telescopes. The dedispersed voltage samples are written to a shared memory ring buffer.

(b) Correlation and folding : Dispersion corrected raw voltage samples read concurrently from the shared memory are correlated to generate the high time resolution visibility time-series. These visibilities are fed into a gating module which bins the data in multiple gates. For a given MSP, while folding using best-fit topocentric rotational model, number of gates and intermediate time resolution of dedispersed visibilities, are empirically adjusted to obtain optimal S/N. In order to retain this optimal S/N in a 1 hr gated image for a 2 ms MSP (considering gate width approximately equal to pulse width), fractional period error per rotation ($\dot{P}$) is required to be below $\sim 10^{-13}$, i.e. MSP period (in ms) is required to be correct up to 7 significant digits. Folding with a fixed topocentric period is sufficient for imaging isolated or loosely coupled binary MSPs. However, we have parameterised the rotational model to include period (P), acceleration ($\dot{P}$) and jerk ($\ddot{P}$) for folding MSPs in tighter orbits. For newly discovered MSPs this topocentric rotational model is derived from PRESTO (Ransom et al. 2002) based periodicity search for the same observation using simultaneously generated incoherent beamformer output. Whereas for MSPs with known ephemeris we have used TEMPO[6] based predictions. The folded visibilities on each gate are then integrated up to a time resolution of 16 seconds and the complex correlation output from each gate are finally written to disks for further processing.

(c) *on-off* gating : The on-pulse gate is also identified using the coherent, or incoherent where the position of the MSP is poorly known, beamformer output, as the arrival time of the pulse is unknown a-priori for new pulsars. The gates containing the pulsed emission are grouped to form the on-pulse data, and the off-pulse data is formed with same number of

[6]http://www.atnf.csiro.au/research/pulsar/tempo

gates covering the off-pulse phases. In order to unambiguously identify location of pulsed emission we have generated *on-off* visibility bin. In addition, by subtracting the nearby off-gate from the on-gate underlying systematics generated from instrumental effects as well as from radio frequency interferences are canceled out, resulting in further improvement in noise statistics.

(d) Calibration and imaging : Coherently dedispersed folded *on-off* visibility data are then flagged for removing the outliers and calibrated for solving the complex gains (Prasad & Chengalur 2011). Calibrated visibilities are imaged and deconvolved using standard imaging package AIPS [7]. MSP is the *only* source in this *on-off* gated image, considering that on and off gates contain equal flux for other sources.

3. Localisation of MSPs using gating correlator

MSP gating correlator is efficient in localising fainter MSPs, where fluxes are around 1 mJy resulting in very low detection significance on continuum image plane (rms noise in 1 hr at GMRT$-$322 $\sim$ 500 μJy). Positional accuracy achieved from *on-off* gated image depends upon hour angle of the observations and S/N of pulsar detection. Considering GMRT$-$322 synthesized beam (FWHM) $\sim$ $10''$, the positional accuracy of a MSP scales according to FWHM/(2$\times$S/N). For a typical S/N of 5 (Table. 2), an accuracy $\pm 1''$, is determined by the AIPS task JMFIT. Such a-priori astrometric accuracy accelerates the convergence in pulsar timing. The newly discovered MSPs have large uncertainties in the a-priori position, requiring timing span of the order of a year to overcome the effect of covariance between position and $\dot{P}$. However, while fitting with more precise a-priori position, having $\pm 1''$ uncertainty, the positional accuracy of $\sim$ 1 mas and a convergence in detection of $\dot{P}$ (with $\Delta\dot{P}/\dot{P} \sim 0.04$) can be achieved in only about 100 days.

We performed gated imaging for five MSPs discovered in Fermi directed radio searches. Among those, PSR J1120$-$3618, J1646$-$2142 and J1828+0625 were discovered by us in GMRT$-$322, whereas PSR J1207$-$5050 in GMRT$-$607 (Ray et al. 2012) and PSR J1551$-$0658 in GBT$-$350 (Bangale et al. 2012). The parameters of these MSPs such as period, DM and mean flux are listed in Table 1. Quoted mean flux is obtained using the simultaneous incoherent beamformer output. For PSR J1207$-$5050 the gating observations were done at 607 MHz while rest of the MSPs were observed at 322 MHz.

PSR J1120$-$3618 is a serendipitously discovered MSP in the GMRT$-$322 field-of-view

[7] http://www.aips.nrao.edu

of known Fermi MSP J1124−3653. This is a very faint MSP (mean flux $\sim$ 300 μJy) in a relatively tighter orbit. PRESTO based search pipeline reports an acceleration equal to 0.1 m/s^2, corresponding to a significant measurement of $\dot{P}$ equal to 2×10^{-12} s/s. This introduces a period (in ms) error at 1 part in 10^5 over 3 hrs of observation, whereas for optimal folding an accuracy up to 1 part in 10^6 over 3 hrs is needed. Thus accounting for acceleration is required to retain the S/N of this MSP in *on-off* gated image plane. The pulse phase is binned in 11 gates (gating window $\sim$ pulse width) at the intermediate time resolution (491.52 μs) of the dedispersed visibilities. The *on-off* gated image for this MSP is shown in Fig. 1. Interestingly this MSP is located at $57'$ offset from the pointing center, which is out-side the GMRT−322 beam-width ($\sim \pm 40'$). To localise the MSP we have performed multi-faceted (Perley 1999) gated imaging which is also corrected for primary beam effect as the pulsar is located at the edge of the beam. In order to obtain the gated image of the full field-of-view, separate facet images are interpolated and averaged onto a larger grid using the AIPS task *FLATN*. A $10'\times10'$ facet of the *on-off* gated image shows the MSP (Fig. 1) with 5σ detection significance, resulting in gated flux of 1.2 mJy which is 4$\times$ the mean flux as expected from gating. The parameters related to gated imaging are listed in Table. 2. Sensitive coherent beam is formed towards the pulsar location by steering the phase center and an expected sensitivity improvement $\sim$ 4$\times$ of incoherent array detection is achieved (Roy et al. 2012).

PSR J1207−5050, J1551−0658, J1646−2142 and J1828+0625 are also successfully localized in their respective *on-off* gated images (shown in Fig. 2). Table. 2 lists the related parameters. PSR J1207−5050 and J1646−2142 are found within the error radius of the associated Fermi sources. Whereas PSR J1551−0658 and J1828+0625 are located at an offset of $20'$ and $26'$ respectively from their pointing centers (outside the error radius), indicating that these MSPs are not likely to be associated with the corresponding gamma-ray sources. Large primary beam of the GBT−350 and large incoherent beam of the GMRT−322 have allowed such serendipitous discoveries. The gated fluxes for all these four MSPs are 3 to 6 times of the respective mean fluxes as expected from the S/N improvement by gating.

4. In-beam phase calibration using pulsar

The sensitive coherent beamformer allows study of high time resolution temporal variations of pulsars. In order to form coherent beam using an array telescope like the GMRT, antenna based complex gains (amplitudes and phases) need to be solved using recorded visibilities on a calibrator source. The optimal baseline length over which the array can be coherently added is limited by the perturbations in ionospheric phases, which are more severe at lower frequencies. Coherent array sensitivity degrades with time due to the tem-

Table 1: Parameters of the concerned MSPs

PSR	Period (ms)	Dispersion measure (pc/cc)	Mean flux^a (mJy)
J1120−3618	5.55	45.1	0.3
J1207−5050	4.84	50.7	0.2
J1551−0658	7.09	21.6	1.0
J1646−2142	5.85	29.7	2.1
J1828+0625	3.63	22.4	1.3

a : Mean flux of PSR J1207−5050 is measured at 607 MHz, rest are in 322 MHz

Table 2: Parameters related to gated imaging

PSR	Gated J2000 position (Errors in $''$)	Offset from pointing centre	Number of gates	Observing duration (min)	Gated flux^a (mJy)	Gated SNR
J1120−3618	$11^h20^m22^s.405$ ($1''.1$); $-36°18'32''.17$ ($2''.2$)	$57'$	11	180	1.2	5
J1207−5050	$12^h07^m21^s.811$ ($0''.4$); $-50°50'30''.27$ ($1''.4$)	$6.2'$	10	120	1.1	6
J1551−0658	$15^h51^m07^s.215$ ($0''.6$); $-06°58'06''.51$ ($0''.6$)	$20'$	14	60	5.8	11
J1646−2142	$16^h46^m18^s.127$ ($0''.9$); $-21°42'08''.96$ ($1''.4$)	$10'$	12	60	11.3	11
J1828+0625	$18^h28^m28^s.030$ ($1''.0$); $06°25'00''.52$ ($1''.3$)	$26'$	15	45	3.5	6

a : Gated flux of PSR J1207−5050 is measured at 607 MHz, rest are in 322 MHz

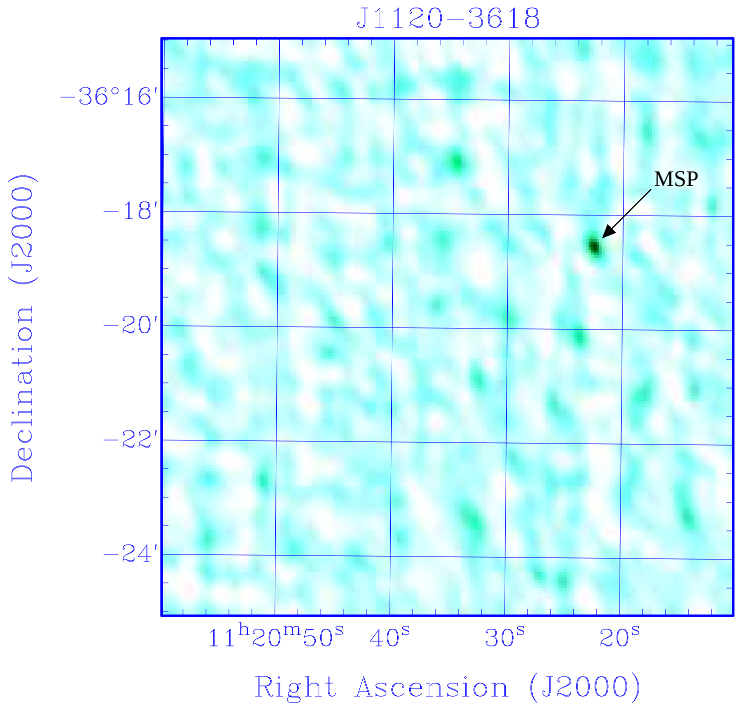

Fig. 1.— Localization of the PSR J1120−3618 using MSP gating correlator. The MSP (marked in the image) is detected in the *on-off* gated image at 57′ offset from pointing centre.

poral decoherences caused by instrumental as well as ionospheric phase fluctuations. Such degradation can be reduced with interleaved calibrator observations. However, applying the phases derived from a distant calibrator into a pulsar field can cause some more decoherences due to underlying different ionospheric inhomogeneities (Thompson et al. 1986). We have used the *on-off* gated image of the target pulsar as a sky model to solve for antenna based residual stochastic phase errors (affecting the data on short time scale) as well as the broad band phase offsets applying self-calibration in AIPS. This process produces a set of phase solutions with time, written in SN table generated by AIPS. While forming the coherent array, these residual phase solutions are recursively applied, in addition to initial narrow-band phase corrections derived from the calibrator visibilities. Background sky subtracted *on-off* gated image of the target pulsar provides a better model to solve for phases since the effects of instrumental as well as RFI artifacts are canceled out. A pulsar with about 10 mJy flux density allows this in-beam calibration process to converge (ensuring more than 3σ detection in each frequency channel during calibration with 10 minutes cadence). This in-beam calibration is the optimal way of coherently adding all the working antennas of an

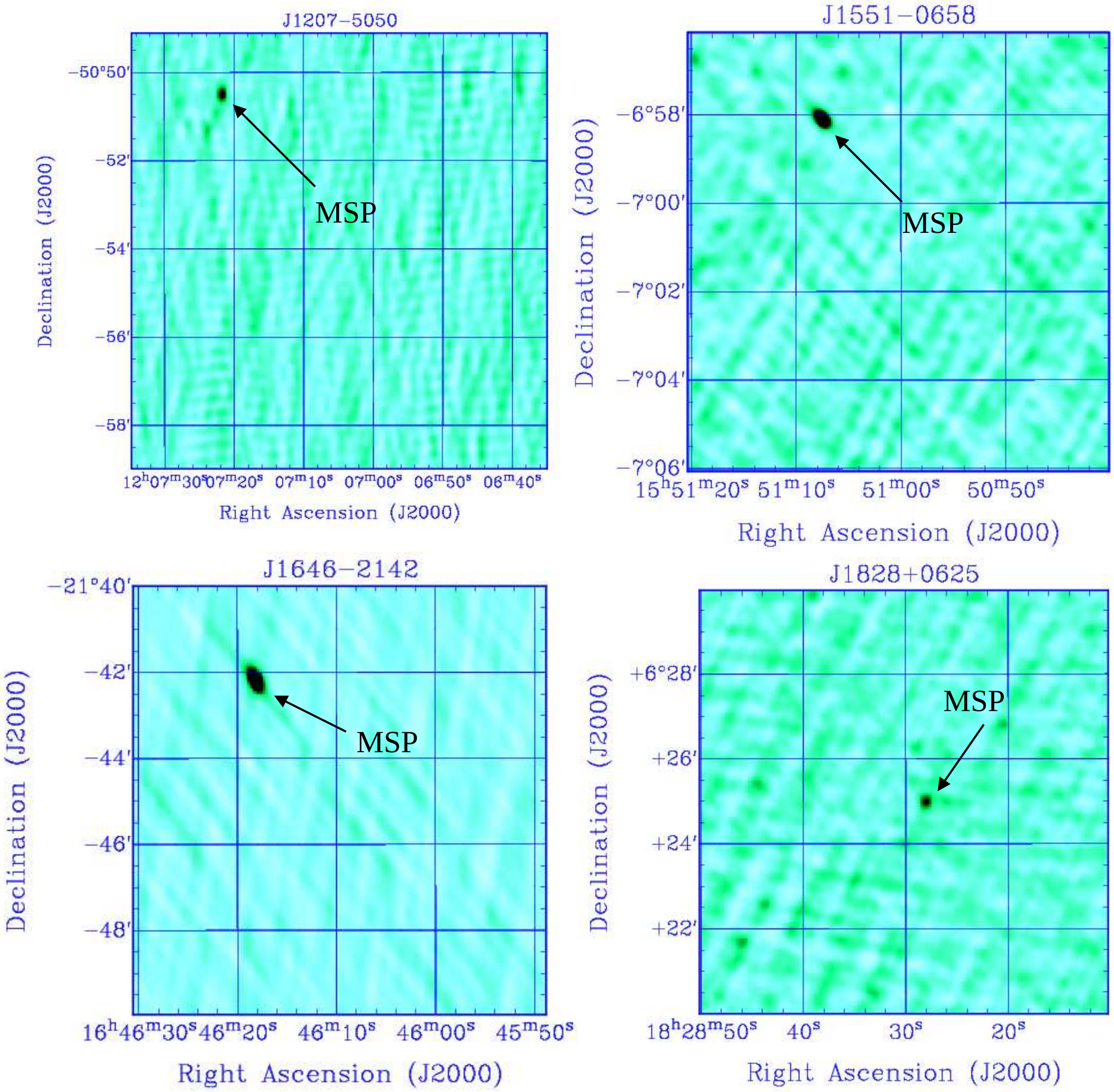

Fig. 2.— The *on-off* gated images for PSR J1207−5050, J1551−0658, J1646−2142 and J1828+0625. All the MSPs are marked in the respective $10' \times 10'$ facet images.

array telescope.

We have generated *on-off* gated image for PSR B1804−08 using 1 minute of base-band data, which is shown in upper left panel of Fig. 3. With the in-beam calibration a sensitivity improvement of 3.5× compared to the conventional coherent array is seen in the folded profile

(upper right panel of Fig. 3). This improvement includes contributions from the increased coherence length of the array (achieved from 50% increase in number of antennas) and better modeling of phase errors. Since the spectral voltages from the antennas are optimally added in phase, the sensitivity improvement can also be visualized as a reduction in the spectral noise in the dispersed pulse phase versus frequency plot (bottom panel of Fig. 3) generated with DSPSR (Straten & Bailes 2010). In addition, the temporal decoherence affecting the long observing scans of target pulsars can be avoided by recursive in-beam calibrations at short time scale, without slewing to a distant calibrator location. Use of pulsar as an in-beam phase calibrator can introduce a lateral shift in the image domain while pulsar is not at the phase centre. This can be calibrated using known position of any in-field catalogue source allowing to perform an astrometric measurement of pulsar.

5. Summary and future scope

We report design and implementation of a coherently dedispersed MSP gating correlator which accounts for a full timing model including orbital motion while folding the visibility time-series. In this paper we have unambiguously determined the precise positions, with $\pm 1''$ accuracy, for five newly discovered MSPs using the *on-off* gated imaging. Locatisations of such relatively fainter MSPs are greatly benefited from the significant enhancement in S/N on the gated image plane compared to the normal synthesis observations. Knowledge of such accurate positions in immediate observations after discovery allows follow-up observations with sensitive coherent array, substantially reducing the use of telescope time by an order of magnitude. Inaccuracy of the astrometric model, associated with large uncertainties in discovery positions, increases the length of data span required to reduce the effect of covariance between position and $\dot{P}$ in timing fit. While determining an unknown binary model, large covariance between position and the binary parameters, specially for long period binaries, can influence the timing fit, which can be minimised with accurate astrometric position ($\sim \pm 1''$). In addition, for pulsars located near the ecliptic plane, the astrometric inaccuracy in ecliptic latitude from the timing fit is much larger (Lorimer & Kramer 2004) indicating the need for interferometric gated observations. This accurate localisation will also facilitate the search for pulsar counterpart and possible binary companions at optical and X-ray. Current astrometric positional accuracy ($\pm 1''$) is decided by array size and S/N of detection. Application of MSP gating correlator in the VLBI (Deller et al. 2009) and the SKA scale improves this a-priori astrometric accuracy (e.g. at 1.4 GHz, 3000 km SKA baseline can give astrometric precision as 15 μas (Smits et al. 2011)).

In addition we have used the *on-off* gated image of the target pulsar to correct the

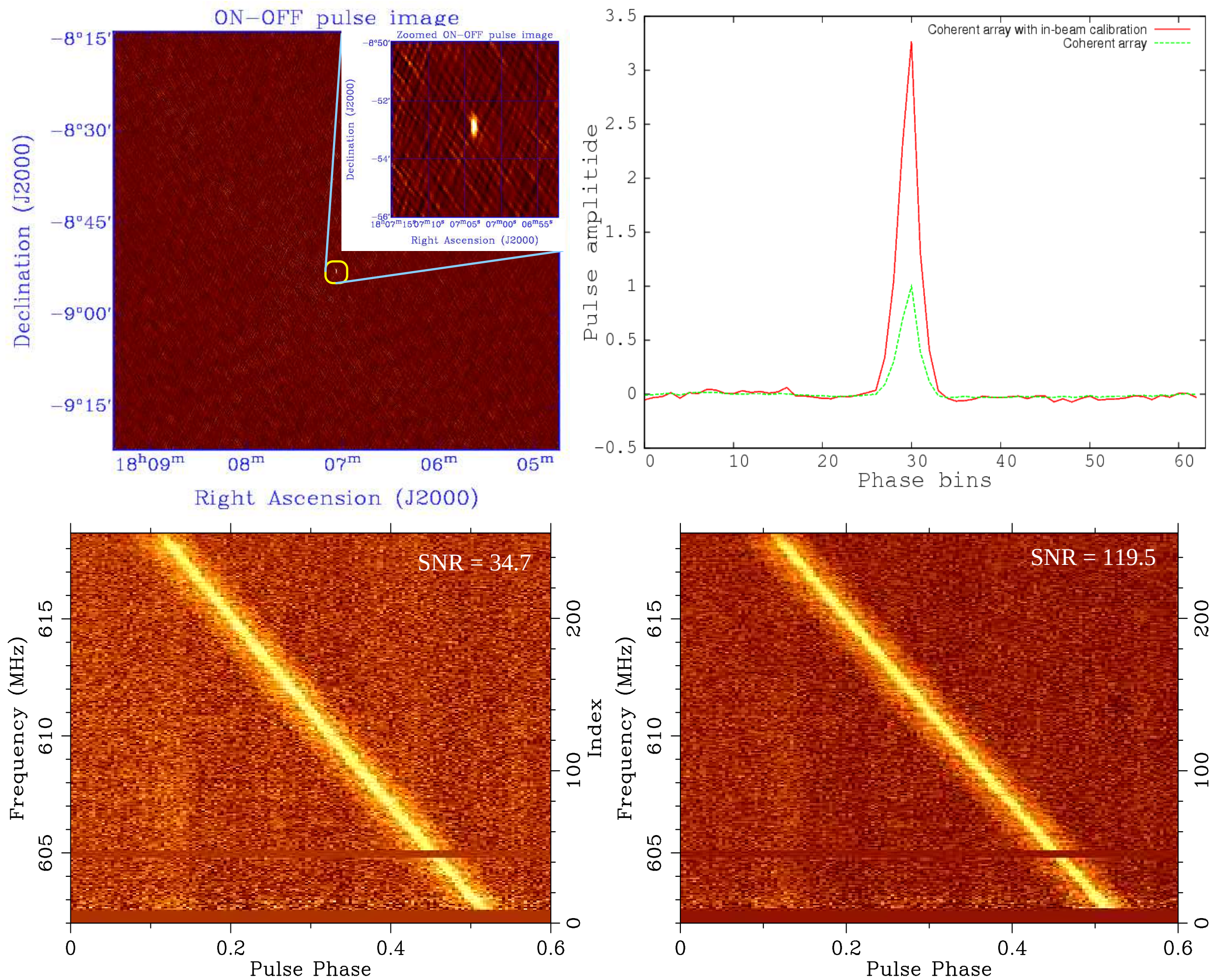

Fig. 3.— In-beam phase calibration using PSR B1804−08. Upper left panel shows the *on-off* gated image with a zoom around the pulsar. Upper right panel shows the coherent array sensitivity improvement in the folded pulse profile using in-beam phase calibration. The dispersed pulse phase with frequency is shown in the bottom panel. The similar sensitivity improvement with reduction of spectral noise (S/N are mentioned on the right corners of the respective plots) is seen on the right panel with respect to the left panel.

residual phase errors in order to avoid degradation of coherent array sensitivity caused by decoherences from instrumental and ionospheric phase fluctuations. Such in-beam phase calibration using a target pulsar ensures optimal sensitivity of the coherent array. We believe that this methodology will be very fruitful for recently commissioned and up-coming array telescopes (e.g. LOFAR, de Vos et al. (2009); MWA, Lonsdale et al. (2009); ASKAP, Johnston et al. (2008); MeerKAT, Jonas (2009)).

Even though the design is primarily motivated by the requirement of localisation of newly discovered Fermi MSPs, this gated imaging has the potential to unfold some other interesting properties of MSPs. Firstly, the MSP gating correlator will allow to perform independent measurement of parallaxes and proper motions even for relatively fainter binary MSPs, which will largely benefit pulsar timing and will probe the interstellar medium (ISM) at various line-of-sight (McGary et al. (2001), Lorimer & Kramer (2004), Smits et al. (2011)). Secondly, the study of un-pulsed emission associated with pulsar wind nebulae (PWN), can be performed by imaging the pulsar field when pulsed emission is off (Gaensler et al. 2000). Angular extent of PWN for high energy pulsars in low density ISM can be as large as few arcminutes (e.g. Frail et al. (1994)), which can be detected with low frequency gated imaging using this MSP gating correlator. Finally, pulsar itself may have a weak off-pulse emission, having magnetospheric origin, coming from close to light cylinder (Perry a& Lyne (1985), Basu et al. (2012)). Origin of possible off-pulse emission from MSPs can be probed with the gated images as a function of pulse longitude and any possible co-location with the gamma-ray emission region will be interesting to investigate. Thus the design of coherently dedispersed MSP gated imaging assures broader scientific returns, while also having importance for SKA applications.

6. Acknowledgments

We thank computer group at GMRT and NCRA. We thank Dr. David Thompson and Dr. Paul Ray for helping us to join PSC and Prof. Yashwant Gupta and Prof. Dipankar Bhattacharya for being members of the GMRT team. We also thank Prof. Ue-Li Pen for insightful discussions and Dr. Maura Mclaughlin for inspiring to work on J1551−0658. We thank the anonymous referee for comments that improved the quality of the paper. We acknowledge support of telescope operators. The GMRT is run by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research.

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This preprint was prepared with the AAS LaTeX macros v5.0.